12 Common-Pool Resources: Commercially Valuable Fisheries

In an overpopulated (or overexploited) world, a system of the commons leads to ruin. . . . Even if an individual fully perceives the ultimate consequences of his actions he is most unlikely to act in any other way, for he cannot count on the restraint his conscience might dictate being matched by a similar restraint on the part of all others.

—Garrett Hardin, *Carrying Capacity as an Ethical Concept* (1967)

Introduction

In 2009, the World Bank and the Food and Agriculture Organization of the United Nations (FAO) released a report called *The Sunken Billions: The Economic Justification for Fisheries Reform*. According to this report, economic losses in marine fisheries due to overfishing, poor management, and economic inefficiency are approximately $50 billion per year (US$). Over the last 30 years, those losses sum to over $2 trillion! The report goes on to argue that well-managed marine fisheries could provide sustainable economic benefits for millions of fisheries and coastal villages and cities. In this chapter we explore the role of economics in designing well-managed fisheries.

Humans share the planet with many other living species. How those biological populations are treated depends in part on whether they are commercially valuable and whether the institutional framework set up to manage the harvesting of that resource provides sufficient conservation incentives to those who are best positioned to protect the resource.

In this chapter, we consider how the process of fisheries management could be reformed to improve both efficiency and sustainability. A commercially valuable species is like a double-edged sword. On one side, the value of the species to humans provides a strong, current reason for human concern about its future. On the other hand, its value may promote excessive harvest. Commercially exploited biological resources can become depleted to the point of extinction if the population is drawn down beyond a critical threshold.

Extinction, although important, is not the only critical renewable resource-management issue. Since any sustainable level of harvest will avoid extinction, how do we choose among them? What sustainable level of harvest is appropriate?

Biological populations belong to a class of renewable resources we will call *interactive resources*, wherein the size of the resource stock (population) is determined jointly by biological considerations and by actions taken by society. The postharvest size of the population, in turn, determines the availability of resources for the future. Thus, humanity's actions affect the flow of these resources over time. Because this flow is not purely a natural phenomenon, the rate of harvest has intertemporal effects. Tomorrow's harvesting choices are affected by today's harvesting behavior.

Using the fishery as a case study, we begin by examining what is meant by an efficient sustainable level of harvest. We then investigate whether efficiency is a sufficiently strong criterion to avoid extinction. Will efficient harvests always result in sustainable outcomes? Having shown how our two social choice criteria apply to fisheries, we turn to an examination of how well our institutions fulfill those criteria. Are normal incentives compatible with efficient sustainable harvest levels?

Unfortunately, we shall discover that in many cases normal incentives are compatible with neither efficiency nor sustainability. Many commercial fisheries can be classified as open access, common–pool resources (Chapter 2), and as such, suffer from overharvesting. The FAO estimates that over 75 percent of the world's fish stocks are either fully exploited or overexploited (FAO, 2009). When the asset value of the resource cannot be protected by existing institutions, a *tragedy of the commons*[1] can result. As we shall see, with so many fisheries experiencing overfishing, finding solutions that meet both efficiency and sustainability criteria is challenging.

Efficient Allocations

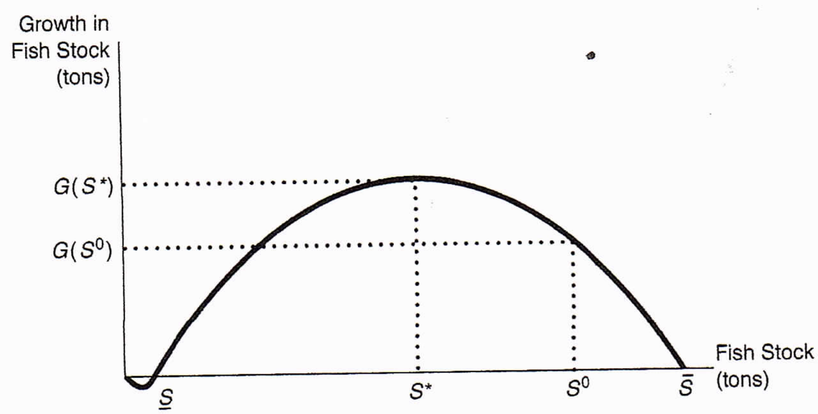
The Biological Dimension

Like many other studies, our characterization of the fishery rests on a biological model originally proposed by Schaefer (1957). The Schaefer model posits a particular average relationship between the growth of the fish population and the size of the fish population. This is an average relationship in the sense that it abstracts from such influences as water temperature and the age structure of the population. The model therefore does not attempt to characterize the fishery on a day-to-day basis, but rather in terms of some long-term average in which these various random influences tend to counterbalance each other (see Figure 12.1).

The size of the population is represented on the horizontal axis and the growth of the population on the vertical axis. The graph suggests that there is a range of population sizes ($\underline{S} - S^*$) where population growth increases as the population increases and a range ($S^* - \overline{S}$) where initial increases in population lead to eventual declines in growth. We can shed further light on this relationship by examining more closely the two points ($\underline{S}$ and $\overline{S}$) where the function intersects the horizontal

[1]Garrett Hardin. "The Tragedy of the Common," *Science* 162 (1968): 1243–1247.

FIGURE 12.1 Relationship between the Fish Population (Stock) and Growth



axis and therefore growth in the stock is zero. $\bar{S}$ is known as the natural equilibrium, since this is population size that would persist in the absence of outside influences. Reductions in the stock due to mortality or out-migration would be exactly offset by increases in the stock due to births, growth of the fish in the remaining stock, and in-migration.

This natural equilibrium would persist because it is stable. A *stable equilibrium* is one in which movements away from this population level set forces in motion to restore it. If, for example, the stock temporarily exceeded $\bar{S}$, it would be exceeding the capacity of its habitat (called *carrying capacity*). As a result, mortality rates or out-migration would increase until the stock was once again within the confines of the carrying capacity of its habitat at $\bar{S}$.

This tendency for the population size to return to $\bar{S}$ works in the other direction as well. Suppose the population is temporarily reduced below $\bar{S}$. Because the stock is now smaller, growth would be positive and the size of the stock would increase. Over time, the fishery would move along the curve to the right until $\bar{S}$ is reached again.

What about the other points on the curve? $\underline{S}$, known as the *minimum viable population*, represents the level of population below which growth in population is negative (deaths and out-migration exceed births and in-migration). In contrast to $\bar{S}$, this equilibrium is unstable. Population sizes to the right of $\underline{S}$ lead to positive growth and a movement along the curve to $\bar{S}$ and away from $\underline{S}$. When the population moves to the left of $\underline{S}$, the population declines until it eventually becomes extinct. In this region, no forces act to return the population to a viable level.

A catch level is said to represent a *sustainable yield* whenever it equals the growth rate of the population, since it can be maintained forever. As long as the population size remains constant, the growth rate (and hence the catch) will remain constant as well.

S^* is known in biology as the *maximum sustainable yield population*, defined as the population size that yields the maximum growth; hence, the maximum sustainable yield (catch) is equal to this maximum growth and it represents the largest catch that can be perpetually sustained. Since the catch is equal to the growth, the sustainable yield for any population size (between $\underline{S}$ and $\overline{S}$) can be determined by drawing a vertical line from the stock size of interest on the horizontal axis to the point at which it intersects the function, and drawing a horizontal line over to the vertical axis. The sustainable yield is the growth in the biomass defined by the intersection of this line with the vertical axis. Thus, in terms of Figure 12.1, $G(S^0)$ is the sustainable yield for population size S^0. Since the catch is equal to the growth, population size (and next year's growth) remains the same.

It should now be clear why $G(S^*)$ is the maximum sustainable yield. Larger catches would be possible in the short run, but these could not be sustained; they would lead to reduced population sizes and eventually, if the population were drawn down to a level smaller than $\underline{S}$, to the extinction of the species.

Static Efficient Sustainable Yield

Is the maximum sustainable yield synonymous with efficiency? The answer is no. Recall that efficiency is associated with maximizing the *net* benefit from the use of the resource. If we are to define the efficient allocation, we must include the costs of harvesting as well as the benefits.

Let's begin by defining the efficient sustainable yield without worrying about discounting. The static efficient sustainable yield is the catch level that, if maintained perpetually, would produce the largest annual net benefit. We shall refer to this as the *static efficient sustainable yield* to distinguish it from the *dynamic efficient sustainable yield*, which incorporates discounting. The initial use of this static concept enables us to fix the necessary relationships firmly in mind before dealing with the more difficult role discounting plays. Subsequently, we raise the question of whether or not efficiency always dictates the choice of a sustainable yield as opposed to a catch that changes over time.

We condition our analysis on three assumptions that simplify the analysis without sacrificing too much realism: (1) the price of fish is constant and does not depend on the amount sold, (2) the marginal cost of a unit of fishing effort is constant, and (3) the amount of fish caught per unit of effort expended is proportional to the size of fish population (the smaller the population, the fewer fish caught per unit of effort).

Given these assumptions, we can build the economic model. Under assumption (3), we can overlay harvest-effort functions onto the population function in Figure 12.1. Since the amount of fish caught per unit effort is held constant, the relationship between catch and stock for given levels of effort can be portrayed by the linear functions in Figure 12.2. (For the mathematically inclined, the formula is Equation 3 in the appendix to this chapter). Notice that increasing effort rotates the harvest function up and to the left (E2 > E1). The sustained yield associated with each level of effort is the point of intersection of these two curves. If we plot the series of points associated with the possible levels of effort and the sustained yield associated with each effort level, we will have our sustainable yield function defined in terms of effort rather than population as portrayed in Figure 12.3. (Effort could be measured in vessel years, hours of fishing, or some other conventional metric.)

To avoid confusion, notice that increasing fishing effort in Figure 12.2 would result in smaller population sizes and would be recorded as a movement from right to left. Because the variable on the horizontal axis in Figure 12.3 is effort, and not population, an increase in fishing effort is recorded as a movement from left to right.

FIGURE 12.2 Relating Equilibrium Effort, Harvest, and Stock Size

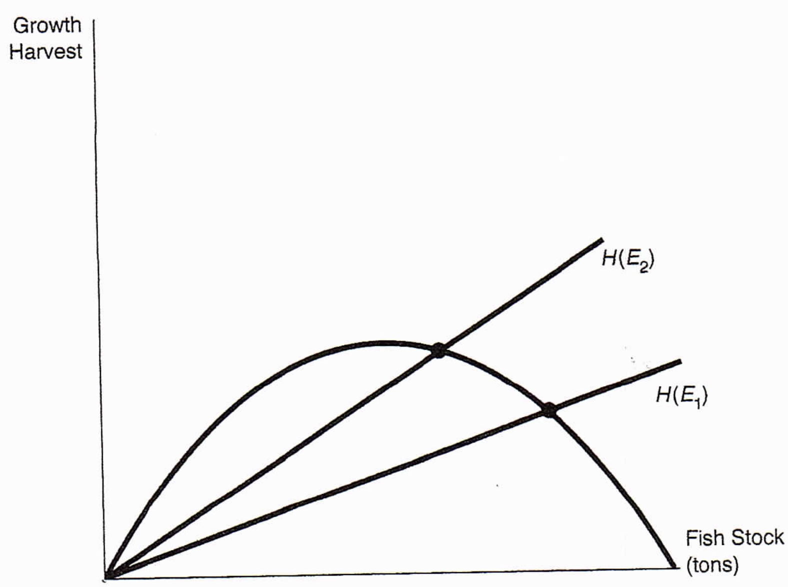
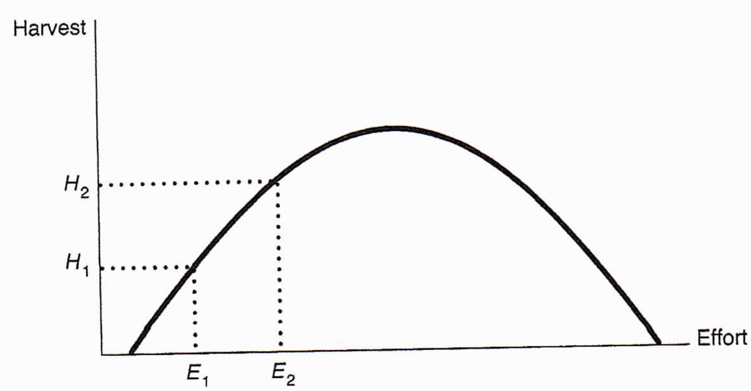


FIGURE 12.3 Sustainable Harvest (Yield)



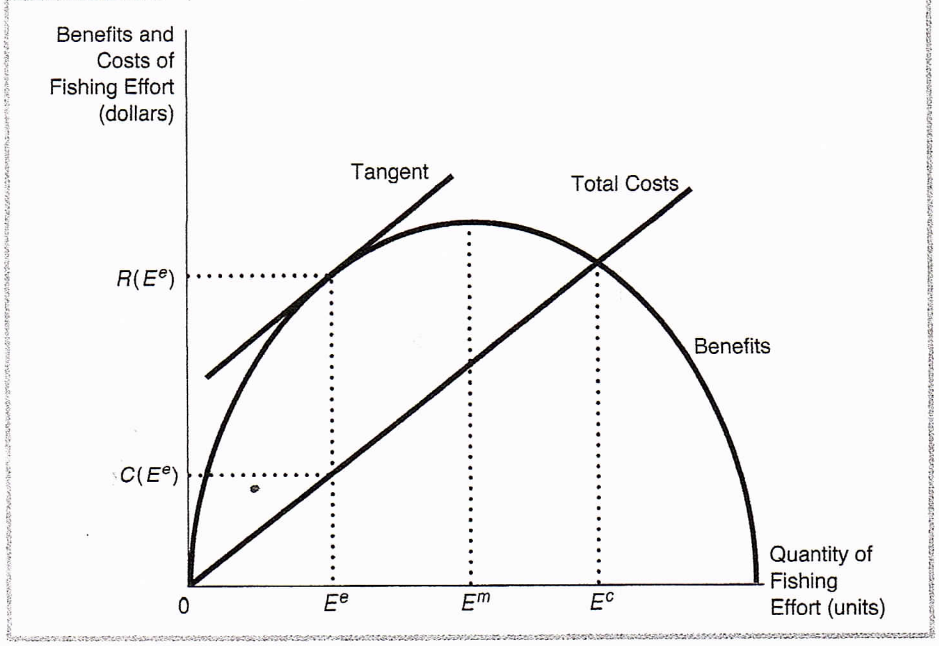
So far so good. To turn this into a complete economic model, we need to determine benefits and costs or, equivalently in this case, total revenue and total costs. From assumption 1 we know that the shape of the biological function dictates the shape of the revenue function. Simply multiplying each sustained yield (harvest) in Figure 12.1 by the constant price, we can turn the physical units (harvest) into monetary units (total revenue). Under assumption 2 we can characterize the final component of our model; the linear function that depicts the total cost is simply calculated as the level of effort times the constant marginal cost of each unit of effort. The resulting figure (12.4) portrays the benefits (revenues) and costs as a function of fishing effort.

In any sustainable yield, annual catches, population, effort levels, and net benefits, by definition, remain constant over time. The static efficient sustainable yield allocation maximizes the constant annual net benefit.

As sustained levels of effort are increased, eventually a point is reached (E^m) at which further effort reduces the sustainable catch (and revenue) for all years. That point, of course, corresponds to the maximum sustainable yield on Figure 12.1 (S^*), meaning that both points reflect the same population and growth levels. Every effort level portrayed in Figures 12.3 and 12.4 corresponds to a specific population level in Figure 12.1.

The net benefit is presented in the diagram as the difference (vertical distance) between benefits (prices times the quantity caught) and costs (the constant marginal cost of effort times the units of effort expended). The efficient level of effort is E^e, that point in Figure 12.4 at which the vertical distance between benefits and costs is maximized.

FIGURE 12.4 Efficient Sustainable Yield for a Fishery



E^e is the efficient level of effort because it is where marginal benefit (which graphically is the slope of the total benefit curve) is equal to marginal cost (the *constant* slope of the total cost curve). Levels of effort higher than E^e are inefficient because the additional cost associated with them exceeds the value of the fish obtained. Can you see why lower levels of effort are also inefficient?

Now we are armed with sufficient information to determine whether or not the maximum sustainable yield is efficient. The answer is clearly no. The maximum sustainable yield would be efficient only if the marginal cost of additional effort were zero. Can you see why? (*Hint*: What is the marginal benefit at the maximum sustainable yield?) Since at E^m the marginal benefit is lower than marginal cost, the efficient level of effort is *less* than that necessary to harvest the maximum sustainable yield. Thus, the static efficient level of effort leads to a *larger* fish population, but a lower annual catch than the maximum sustainable yield level of effort.

To fix these concepts firmly in mind, consider what would happen to the static efficient sustainable yield if a technological change were to occur (e.g., sonar detection) that lowered the marginal cost of fishing. The lower marginal cost would result in a rotation of the total cost curve to the right. With this new cost structure, the old level of effort would no longer be efficient. The marginal cost of fishing (slope of the total cost curve) would now be lower than the marginal benefit (slope of the total benefit curve). Since the marginal cost is constant, the equality of marginal cost and marginal benefit can result only from a decline in marginal benefits. This implies an increase in effort. The new static efficient sustainable yield equilibrium implies more annual effort, a lower population level, a larger annual catch, and a higher net benefit for the fishery.

Dynamic Efficient Sustainable Yield

The static efficient sustainable yield turns out to be the special case of the dynamic efficient sustained yield where the discount rate is zero. It is not difficult to understand why; the static efficient sustained yield is the allocation that maximizes the (identical) net benefit in every period. Any effort levels higher than this would yield temporarily larger catches (and net benefit), but this would be more than offset by a reduced net benefit in the future as the stock reached its new lower level. Thus, the undiscounted net benefits would be reduced.

The effect of a positive discount rate for the management of a fishery is similar to its influence on the allocation of depletable resources—the higher the discount rate, the higher the cost (in terms of forgone current income) to the resource owner of maintaining any given resource stock. When positive discount rates are introduced, the efficient level of effort would be increased beyond that suggested by the static efficient sustained yield with a corresponding decrease in the equilibrium population level.

The increase in the yearly effort beyond the efficient sustained yield level would *initially* result in an increased net benefit from the increased catch. (Remember that the amount of fish caught per unit effort expended is proportional to the size of the population.) However, since this catch exceeds the sustained yield for that population size, the population of fish would be reduced and future population and catch levels would be lower. Eventually, as that level of effort is maintained, a new, lower equilibrium level would be attained when the size of the catch once again equals the growth of the population. Colin Clark (1976) has shown mathematically that in terms of Figure 12.4, as the discount rate is increased, the dynamic efficient level of effort is increased until, with an infinite discount rate, it would become equal to E^c, the point at which net benefits go to zero.

It is easy to see why the use of an infinite discount rate to define the dynamic efficient sustained yield results in allocation E^c. We have seen that temporally interdependent allocations over time give rise to a marginal user cost measuring the opportunity cost of increasing current effort. This opportunity cost reflects the forgone future net benefits when more resources are extracted in the present. For efficient interdependent allocations, the marginal willingness to pay is equal to the marginal user cost plus the marginal cost of extraction.

With an infinite discount rate, this marginal user cost is zero, because no value is received from future allocations. (Do you see why?) This implies that (1) the marginal cost of extraction equals the marginal willingness to pay, which equals the constant price, and (2) total benefits equal total costs.[2] Earlier we demonstrated that the static efficient sustained yield implies a larger fish population than the maximum sustained yield. Once discounting is introduced, it is inevitable that the dynamic efficient sustained yield would imply a smaller fish population than the static efficient sustained yield and it is possible, though not inevitable, that the sustained catch would be smaller. Can you see why? In Figure 12.4 the sustained catch clearly is lower for an infinite discount rate.

The likelihood of the population being reduced below the level supplying the maximum sustainable yield depends on the discount rate. In general, the lower the extraction costs and the higher the discount rate, the more likely it is that the dynamic efficient level of effort will exceed the level of effort associated with the maximum sustainable yield. This is not difficult to see if we remember the limiting case discussed earlier. When the marginal extraction cost is zero, the static efficient sustainable yield and the maximum sustainable yield are equal.

Thus, with zero marginal extraction costs and a positive discount rate, the dynamic efficient level of effort necessarily exceeds not only the static efficient level of effort, but also the level of effort associated with the maximum sustainable yield. Higher extraction costs reduce the static efficient sustainable yield but not

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[2]This is not difficult to demonstrate mathematically. In our model, the yield (h) can be expressed as $h = qES$, where q is the proportion of the population harvested with one unit of effort, S is the size of the population, and E is the level of effort. One of the conditions a dynamic efficient allocation has to satisfy with an infinite discount rate is $P = a/qS$, where P is the constant price, a is the constant marginal cost per unit of effort, and qS is the number of fish harvested per unit of effort. By multiplying both sides of this equation by h and collecting terms, we obtain $Ph = aE$. The left-hand side is total benefits, while the right is total cost, implying net benefits are zero.

the maximum sustainable yield. (Remember that it is a biological, not an economic, concept.) By reducing efficient effort levels, higher extraction costs reduce the likelihood that discounting would cause the population to be drawn below the maximum sustainable yield level.

Would a dynamically efficient management scheme lead to extinction of the fishery? As Figure 12.4 shows, it would not be possible under the circumstances described here because E^c is the highest dynamically efficient level possible in this model, and that level falls well short of the level needed to drive the population to extinction. However, in more complex models, extinction certainly can be an outcome.

For extinction to occur under a dynamic efficient management scheme, the benefit from extracting the very last unit would have to exceed the cost of extracting that unit (including the costs on future generations). As long as the population growth rate exceeds the discount rate, this will not be the case. If, however, the growth rate is lower than the discount rate, extinction can occur even in an efficient management scheme if the costs of extracting the last unit are sufficiently low.

Why does the biomass rate of growth have anything to do with whether or not an efficient catch profile leads to extinction? Rates of growth determine the productivity of conservation efforts.[3] With high rates of growth, future generations can be easily satisfied. On the other hand, when the rate of growth is very low, it takes a large sacrifice by current generations to produce more fish for future generations. In the limiting case, where the rate of growth is zero, we have a resource with fixed supply and therefore this fishery would become an exhaustible resource. Total depletion would occur whenever the price commanded by the resource is high enough to cover the marginal cost of extracting the last unit.

We have shown that the dynamic efficiency criterion is not automatically consistent with sustaining constant yields perpetually for an interactive renewable resource, since it is mathematically possible for an efficient allocation of a fishery to lead to extinction of the resource. How likely are these criteria to conflict in practice?

It is not as likely as this basic model might imply. Actual fisheries differ from the standard model in two key ways. First, harvesting marginal costs are typically not constant (as they are in the model discussed previously), but rather increase as the remaining stock size diminishes. Second, while the model we discussed holds prices constant, the size of the harvest can affect prices; larger harvests can depress them. Both of these modifications of the basic model suggest additional incentives for conserving the stock.

How empirically important are these incentives? Grafton et al. (2007) examine their importance for four specific fisheries and find not only that extinction is not the efficient outcome in any of the four fisheries but also in general, in this

[3]Note the parallel with the role of the growth rate in efficient timber harvesting in Chapter 11.

reformulated model, the stock level that maximizes the present value of net benefits is actually *larger* than the stock level that supports the maximum sustainable yield. Their results seem to hold both for relatively high discount rates and relatively long-lived fish. (The orange roughy fishery, discussed in more detail below, was one of the four they studied.)

Appropriability and Market Solutions

We have defined an efficient allocation of the fishery over time. The next step is to characterize the normal market allocation and to contrast these two allocations. Where they differ we can entertain the possibility of various public policy corrective means.

Let's first consider the allocation resulting from a fishery managed by a competitive sole owner. A sole owner would have a well-defined property right to the fish. We can establish the behavior of a sole owner by elaborating on Figure 12.4 as is done in Figure 12.5. Note that the two panels share a common horizontal axis, a characteristic that allows us to examine the effect of various fishing effort levels on both graphs.

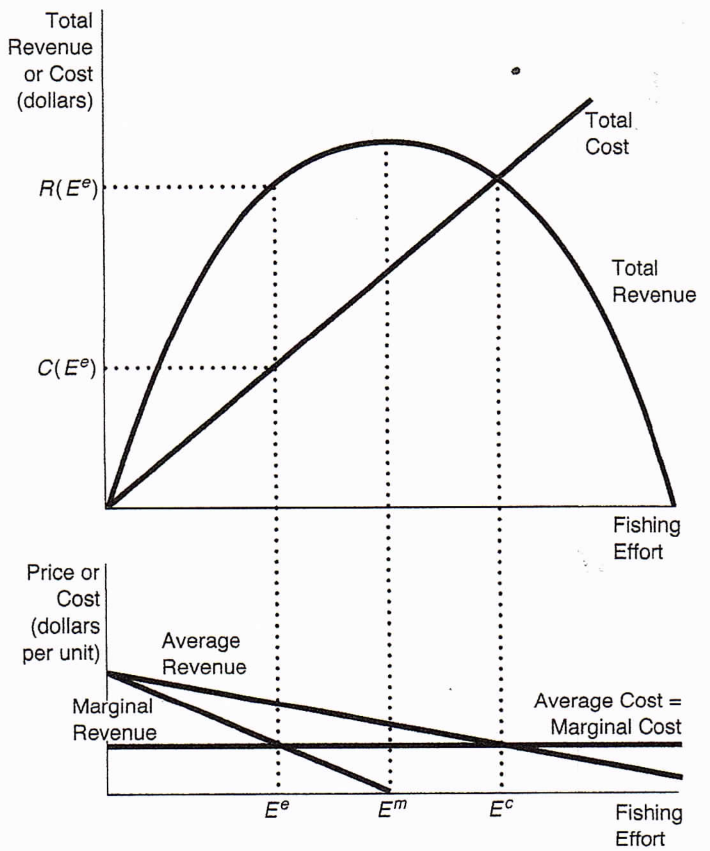
A sole owner would want to maximize his or her profits. Ignoring discounting for the moment, the owner can increase profits by increasing fishing effort until marginal revenue equals marginal cost. This occurs at effort level E^e, the static efficient sustainable yield, and yields positive profits equal to the difference between $R(E^e)$ and $C(E^e)$.

In ocean fisheries, however, sole owners are unlikely. Ocean fisheries are typically open-access resources—no one exercises complete control over them. Since the property rights to the fishery are not conveyed to any single owner, no fisherman can exclude others from exploiting the fishery.

What problems arise when access to the fishery is completely unrestricted? Open-access resources create two kinds of external costs: a contemporaneous external cost and an intergenerational external cost. The contemporaneous external cost, which is borne by the current generation, involves the overcommitment of resources to fishing—too many boats, too many fishermen, too much effort. As a result, current fishermen earn a substantially lower rate of return on their efforts. The intergenerational external cost, borne by future generations, occurs because overfishing reduces the stock, which, in turn, lowers future profits from fishing.[4]

[4]This will result in fewer fish for future generations as well as smaller profits if the resulting effort level exceeds that associated with the maximum sustainable yield. If the open-access effort level is lower than the maximum sustainable yield effort level (when extraction costs are very high), then reductions in stock would increase the growth in the stock, thus supplying more fish (albeit lower net benefits) to future generations.

FIGURE 12.5 Market Allocation in a Fishery



We can use Figure 12.5 to see how these external costs arise.[5] Once too many fishermen have unlimited access to the same common-pool fishery, the property rights to the fish are no longer efficiently defined. At the efficient level, each boat would receive a profit equal to its share of the scarcity rent. This rent, however, serves as a stimulus for new fishermen to enter, pushing up costs and eliminating the rent. Open access results in overexploitation.

The sole owner chooses not to expend more effort than E^e because to do so would reduce the profits of the fishery, resulting in a personal loss to her. When access to the fishery is unrestricted, a decision to expend effort beyond E^e reduces profits to the fishery as a whole but not to that individual fisherman. Most of the decline in profits falls on the other fishermen.

[5]This type of analysis was first used in Gordon (1954).

In an open-access resource, the individual fisherman has an incentive to expend further effort until profits are zero. In Figure 12.5, that point is at effort level E^c, at which average revenue and average cost are equal. It is now easy to see the contemporaneous external cost—too much effort is being expended to catch too few fish, and the cost is substantially higher than it would be in an efficient allocation.

If this point seems abstract, it shouldn't. Many fisheries are currently plagued by precisely these problems. In a productive fishery in the Bering Sea and Aleutian Islands, for example, one study (Huppert, 1990) found significant overcapitalization. While the efficient number of motherships (used to take on and process the catch at sea, so the catch boats do not have to return to port as often) was estimated to be 9, the actual level was 140. As a result, a significant amount of net benefits was lost ($124 million a year). Had the fishery been harvested more slowly, the same catch could have been achieved with fewer boats used closer to their capacity.

In Chapter 2, we stated that the resource owner with exclusive property rights balances the use value against the asset value. When access to the resource is unrestricted, exclusivity is lost. As a result, it is rational for a fisherman to ignore the asset value, since he or she can never appropriate it, and simply maximize the use value. In the process, all the scarcity rent is dissipated. The allocation that results from allowing unrestricted access to the fishery is identical to that resulting from a dynamic efficient sustainable yield when an infinite discount rate is used.

Open-access resources do not automatically lead to a stock lower than (S^*), the one that maximizes the sustained yield. It is possible to draw a cost function with a slope sufficiently steep that it intersects the benefit curve at a point to the left of E^m. Nonetheless, mature, open-access fisheries can be exploited well beyond the point of maximum sustainable yield.

Open-access fishing may or may not pose the threat of species extinction. It depends on the nature of the species and the benefits and costs of an effort level above E^m that would have the effect of driving the stock level below the minimum viable population. Consider the northern bluefin tuna, for example. Considered critically endangered, it is still being harvested at unsustainable levels due to the high market price fishermen receive as a result of its popularity in sushi restaurants. Since the threat of extinction cannot be determined purely from theory, it must be determined by empirical studies on a case-by-case basis.

Are open-access resources and common-pool resources synonymous concepts? They are not. Not all common-pool resources allow unlimited access. Informal arrangements among those harvesting the common-pool resource, which may be fostered by harvester cooperation, can serve to limit access (Example 12.1 presents one such arrangement).

Open-access resources generally violate the efficiency criterion and may violate the sustainability criteria. If these criteria are to be fulfilled, some restructuring of the decision-making environment may be necessary. The next section examines the possible role for government in how that can be accomplished.

EXAMPLE 12.1

Harbor Gangs of Maine and Other Informal Arrangements

Unlimited access to common-pool resources reduces net benefits so drastically that this loss encourages those harvesting the resource to band together to restrict access, if possible. The Maine lobster fishery is one setting where those informal arrangements have served to limit access with some considerable success.

Key among these arrangements is a system of territories that establishes boundaries between fishing areas. Particularly near the off-shore islands, these territories tend to be exclusively harvested by close-knit, disciplined groups of harvesters. These "gangs" restrict access to their territory by various means. (Some methods, although effective, are covert and illegal, such as the practice of cutting the lines to lobster traps owned by new entrants, thereby rendering the traps irretrievable.)

Acheson (2003) found that in every season of the year, the pounds of lobster caught per trap and the size of those lobsters were greater in defended areas. Not only did the larger number of pounds result in more revenue, but also the bigger lobsters brought in a higher price per pound. Informal arrangements were successful in this case, in part, because the Maine lobster stock is also protected by regulations limiting the size of lobsters that can be taken (imposing both minimum and maximum sizes) and prohibiting the harvest of egg-bearing females.

It turns out that many other examples of community *co-management* also offer encouraging evidence for the potential of sustainability. One example, the Chilean abalone (a type of snail called *loco*) is Chile's most valuable fishery. Local fishers began cooperating in 1988 to manage a small stretch (2 miles) of coastline. Today, the co-management scheme involves 700 co-managed areas, 20,000 artisanal fishers, and 2500 miles of coastline.

While it would be a mistake to assume that all common-pool resources are characterized by open access, it would also be a mistake to assume that all informal co-management arrangements automatically provide sufficient social means for producing efficient harvests such that stronger public policy would be unnecessary. A recent study (Gutiérrez et al., 2011) examined 130 fisheries in 44 developed and developing countries. It found that co-management can work, but only in the presence of strong leadership, social cohesion, and complementary incentives such as individual or community quotas. They find that effective community-based co-management can both sustain the resource and protect the livelihoods of nearby fishermen and fishing communities. The existence of nearby protected areas was also found to be an important determinant of success.

Source: Acheson. J. M. (2003). *Capturing the commons: Devising institutions to manage the Maine lobster fishery*. Hanover, NH: University Press of New England.; Gutiérrez, N. L., Hilborn, R., & Omar Defeo, O. (January 5, 2011). Leadership, social capital and incentives promote successful fisheries. *Nature, 470,* 386–389(17 February 2011) doi:10.1038/nature09689. Retrieved from http://www.nature.com/nature/journal/v470/n7334/full/nature09689.html

Public Policy Toward Fisheries

What can be done? A variety of public policy responses is possible. Perhaps it is appropriate to start with circumstances where allowing the market to work can improve the situation.

Raising the Real Cost of Fishing

Perhaps one of the best ways to illustrate the virtues of using economic analysis to help design policies is to show the harsh effects of policy approaches that ignore it. Because the earliest approaches to fishery management had a single-minded focus on attaining the maximum sustainable yield, with little or no thought given to maximizing the net benefit, they provide a useful contrast.

One striking concrete example is the set of policies originally designed to deal with overexploitation of the Pacific salmon fishery in the United States. The Pacific salmon is particularly vulnerable to overexploitation and even extinction because of its migration patterns. Pacific salmon are spawned in the gravel beds of rivers. As juvenile fish, they migrate to the ocean, only to return as adults to spawn in the rivers of their birth. After spawning, they die. When the adults swim upstream, with an instinctual need to return to their native streams, they can easily be captured by traps, nets, or other catching devices.

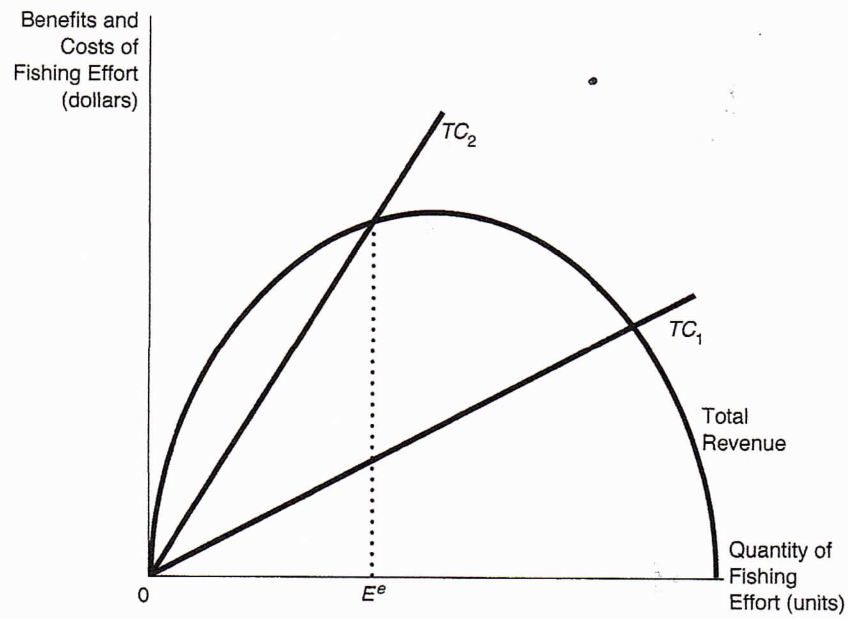
Recognizing the urgency of the problem, the government took action. To reduce the catch, they raised the cost of fishing. Initially this was accomplished by preventing the use of any barricades on the rivers and by prohibiting the use of traps (the most efficient catching devices) in the most productive areas. These measures proved insufficient, since mobile techniques (trolling, nets, and so on) proved quite capable by themselves of overexploiting the resource. Officials then began to close designated fishing areas and suspend fishing in other areas for certain periods of time. In Figure 12.4, these measures would be reflected as a rotation of the total cost curve to the left until it intersected the total benefits (revenue) curve at a level of effort equal to E^e. The aggregate of all these regulations had the desired effect of curtailing the yield of salmon.

Were these policies efficient? They were not even though they resulted in the efficient catch! This statement may seem inconsistent, but it is not. Efficiency implies not only that the catch must be at the efficient level, but also it must be extracted at the lowest possible cost. It was this condition that was violated by these policies (see Figure 12.6).

Figure 12.6 reflects the total cost in an unregulated fishery (TC_1) and the total cost after these policies were imposed (TC_2). The net benefit received from an efficient policy is shown graphically as the vertical distance between total cost and total benefit. After the policy, however, the net benefit was reduced to zero; the net benefit (represented by vertical distance) was lost to society. Why?

The net benefit was squandered on the use of excessively expensive means to catch the desired yield of fish. Rather than use traps to reduce the cost of catching

FIGURE 12.6 Effect of Regulation



the desired number of fish, traps were prohibited. Larger expenditures on capital and labor were required to catch the same number of fish. This additional capital and labor represent one source of the waste.

The limitations on fishing times had a similar effect on cost. Rather than allowing fishermen to spread their effort out over time so the boats and equipment could be more productively utilized, fishermen were forced to buy larger boats to allow them to take as much as possible during the shorter seasons. (As one extreme example, Tillion (1985) reported that the 1982 herring season in Prince William Sound lasted only four hours and the catch still exceeded the area quota.) Significant overcapitalization produced gross inefficiency.

Regulation imposed other costs as well. It was soon discovered that while the above regulations were adequate to protect the depletion of the fish population, they failed to curb the incentive for individual fishermen to increase their share of the take. Even though the profits would be small because of high costs, new technological change would allow adopters to increase their shares of the market and put others out of business.

To protect themselves, the fishermen were eventually successful in introducing bans on new technology. These restrictions took various forms, but two are particularly noteworthy. The first was the banning of the use of thin-stranded, monofilament net. The coarse-stranded net it would have replaced was visible to the salmon in the daytime and therefore could be avoided by them. As a result, it was useful only at night. By contrast, the thinner monofilament nets could be successfully used during the daylight hours as well as at night. Monofilament nets were banned in Canada and the United States soon after they appeared.

The most flagrantly inefficient regulation was one in Alaska that barred gill netters in Bristol Bay from using engines to propel their boats. This regulation lasted until the 1950s and heightened the public's awareness of the anachronistic nature of this regulatory approach. The world's most technologically advanced nation was reaping its harvest from the Bering Sea in sailboats, while the rest of the world—particularly Japan and the Soviet Union—was modernizing their fishing fleets at a torrid pace!

Time-restriction regulations had a similar effect. Limiting fishing time provides an incentive to use that time as intensively as possible. Huge boats facilitate large harvests within the period and therefore are profitable but are very inefficient; the same harvest could normally be achieved with fewer, smaller (less expensive) boats used to their optimum capacity.

Guided by a narrow focus on biologically determined sustainable yield that ignored costs, these policies led to a substantial loss in the net benefit received from the fishery. Costs are an important dimension of the problem, and when they are ignored, the incomes of fishermen suffer. When incomes suffer, further conservation measures become more difficult to implement, and incentives to violate the regulations are intensified.

Technical change presents a further problem, with attempts to use cost-increasing regulations to reduce fishing effort. Technical innovations can lower the cost of fishing, thereby offsetting the increases imposed by the regulations. In the New England fishery, for example, Jin et al. (2002) report that the introduction of new technologies such as fishfinders and electronic navigation aids in the 1970s and 1980s led to higher catches and declines in the abundance of the stocks despite the extensive controls in place at the time.

Taxes

Is it possible to provide incentives for cost reduction while assuring that the yield is reduced to the efficient level? Can a more efficient policy be devised? Economists who have studied the question believe that more efficient policies are possible.

Consider a tax on effort. In Figure 12.6, taxes on effort would also be represented as a rotation of the total cost line and the after-tax cost to the fishermen would be represented by line TC_2. Since the after-tax curve coincides with TC_2, the cost curve for all those inefficient regulations, doesn't this imply that the tax system is just as inefficient? No! The key to understanding the difference is the distinction between *transfer costs* and *real resource costs.*

Under a regulation system of the type described earlier in this chapter, all of the costs included in TC_2 are real resource costs, which involve utilization of resources. Transfer costs, by contrast, involve transfers of resources from one part of society to another, rather than their dissipation. Transfers do represent costs to that part of society bearing them, but are exactly offset by the gain received by the recipients.

Unlike real resource costs, resources are not used up with transfers. Thus, the calculation of the size of the net benefit should subtract real-resource costs, but not transfer costs, from benefits. For society as a whole, transfer costs are retained as part of the net benefit; only who receives them is affected.

In Figure 12.6, the net benefit under a tax system is identical to that under an efficient allocation. The net benefit represents a transfer cost to the fisherman that is exactly offset by the revenues received by the tax collector. This discussion should not obscure the fact that, as far as the individual fisherman is concerned, tax payments are very real costs. Rent normally received by a sole owner is now received by the government. Since the tax revenues involved can be substantial, fishermen wishing to have the fishery efficiently managed may object to this particular way of doing it. They would prefer a policy that restricts catches while allowing them to keep the rents. Is that possible?

Catch Share Programs

Catch share programs offer this option. The Magnuson Stevens Act authorizes several types of catch share approaches under its "limited access privilege" program. All of them allocate a portion of the total allowable catch to individuals, communities, or cooperatives. Programs in this category include individual fishing quotas (IFQs), individual transferable quotas (ITQs), and territorial use rights fisheries (TURFs).[6] An ITQ program is a specific IFQ program where harvesting privileges can be transferred subsequent to initial allocations, while TURFs grant rights to a geographic area. All of these create a type of harvest entitlement either in the fishery as a whole or in a specific geographic area. By 2012, all U.S. fisheries were covered by annual catch limits.

ITQs. Let's first consider individual transferable quotas. Several of their identifiable characteristics serve to enhance efficiency:

1. The quotas entitle the holder to catch a specified share of the total authorized catch of a specified type of fish.
2. The catch authorized by the quotas held by all fishermen should be equal to the efficient catch for the fishery.
3. The quotas should be freely transferable among fishermen and markets should send appropriate price signals about the value of the fishery.

Each of these three characteristics plays an important role in obtaining an efficient allocation. Suppose, for example, the quota was defined in terms of the right to own and use a fishing boat rather than in terms of catch—not an uncommon type of quota. Such a quota is not efficient because under this type of quota an inefficient incentive still remains for each boat owner to build larger boats, to place extra equipment on them, and to spend more time fishing. These actions would expand the capacity of each boat and cause the actual catch to exceed the target

[6]NOAA Catch Share Policy, *Executive Summary, 2013*. Retrieved from http://www.nmfs.noaa.gov/sfa/domes_fish/catchshare/docs/noaa_cs_policy.pdf

(efficient) catch. In a nutshell, the boat quota limits the number of boats fishing but does not limit the amount of fish caught by each boat. If we are to reach and sustain an efficient allocation, it is the catch that must ultimately be limited.

While the purpose of the second characteristic is obvious, the role of transferability deserves more consideration. With transferability, the entitlement to fish flows naturally to those gaining the most benefit from it because their costs are lower. Because it is valuable, the transferable quota commands a positive price. Those who have quotas but also have high costs find they make more money selling the quotas than using them. Meanwhile, those who have lower costs find they can purchase more quotas and still make money.

Transferable quotas also encourage technological progress. Adopters of new cost-reducing technologies can make more money on their existing quotas and make it profitable to purchase new quotas from others who have not adopted the technology. Therefore, in marked contrast to the earlier regulatory methods used to raise costs, both the tax system and the transferable quota system encourage the development of new technologies.

How about the distribution of the rent? In a quota system, the distribution of the rent depends crucially on how the quotas are initially allocated. There are many possibilities with different outcomes. The first possibility is for the government to auction off these quotas. With an auction, government would appropriate all the rent and the outcome would be very similar to the outcome of the tax system. If the fishermen do not like the tax system, they would not like the auction system either.

In an alternative approach, the government could give the quotas to the fishermen, for example, in proportion to their historical catch. The fishermen could then trade among themselves until a market equilibrium is reached. All the rent would be retained by the current generation of fishermen. Fishermen who might want to enter the market would have to purchase the quotas from existing fishermen. Competition among the potential purchasers would drive up the price of the transferable quotas until it reflected the market value of future rents, appropriately discounted.[7]

Thus, this type of quota system allows the rent to remain with the fishermen, but only the current generation of fishermen. Future generations see little difference between this quota system and a tax system; in either case, they have to pay to enter the industry, whether it is through the tax system or by purchasing the quotas.

In 1986, a limited ITQ system was established in New Zealand to protect its deepwater trawl fishery (Newell et al., 2005). Although this was far from being the only, or even the earliest, application of ITQs (see Table 12.1), it is the world's largest and provides an unusually rich opportunity to study how this approach works in practice. Some 130 species are fished commercially in

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[7] This occurs because the maximum bid any potential entrant would make is the value to be derived from owning that permit. This value is equal to the present value of future rents (the difference between price and marginal cost for each unit of fish sold). Competition will force the purchaser to bid near that maximum value, lest he or she lose the quota.

TABLE 12.1 Countries with Individual Transferable Quota Systems

Country	Number of Species Covered
Argentina	1
Australia	26
Canada	52
Chile	9
Denmark	1
Estonia	2
Falkland Islands	4
Greenland	1
Iceland	25
Italy	1
Morocco	1*
Mozambique	4
Namibia	10
The Netherlands	7
New Zealand	97
Portugal	1*
South Africa	1*
United States	6

*Complete species list unavailable. Norway, Peru, and Russia also use ITQ systems as part of their fisheries management.

Source: Adapted from Chu, C. (2009). Thirty years later: The global growth of ITQs and their influence on stock status in marine fisheries. *Fish and Fisheries, 10*,217–230; Arnason, R. (Summer 2012). Property rights in fisheries: How much can individual transferable quotas accomplish? *Review of Environmental Economics and Policy. 6*(2), 217–236.

New Zealand.[8] The Fisheries Amendment Act of 1986 that set up the program covered 17 inshore species and 9 offshore species. By 2004, it had expanded to cover 70 species. Newell et al. (2005) found that the export value of these species ranged from NZ $700/metric ton for jack mackerel to NZ $40,000/metric ton for rock lobster.[9]

Because this program was newly developed, allocating the quotas proved relatively easy. The New Zealand Economic Exclusion Zone (EEZ) was divided geographically into quota-management regions. The total allowable catches (TACs) for the seven basic species were divided into individual transferable quotas by quota-management regions. By 2000, 275 quota markets were in existence.

[8]Ministry of Fisheries, New Zealand, www.fish.govt.nz.

[9]The New Zealand Ministry of Fisheries reports that the average quota increased in value from $2.7 billion in 1996 to $3.8 billion in 2007.

Quotas were initially allocated to existing firms based on their average catch over the period from 1982 to 1984. The rights to harvest were denominated in terms of a specific amount of fish, but were granted only for a 10-year period. At the same time as the deep-sea fishery policy was being developed, the inshore fishery began to fall on hard times. Too many participants were chasing too few fish. Some particularly desirable fish species were being seriously overfished. While the need to reduce the amount of pressure being put on the population was rather obvious, the means to accomplish that reduction was not at all obvious. Although it was relatively easy to prevent new fishermen from entering the fisheries, it was harder to figure out how to reduce the pressure from those who had been fishing in the area for years or even decades. Because fishing is characterized by economies of scale, simply reducing everyone's catch proportionately wouldn't make much sense. That would simply place higher costs on everyone and waste a great deal of fishing capacity as all boats sat around idle for a significant proportion of time. A better solution would clearly be to have fewer boats harvesting the stock. That way each boat could be used closer to its full capacity without depleting the population. Which fishermen should be asked to give up their livelihood and leave the industry?

The economic-incentive approach addressed this problem by having the government buy back catch quotas from those willing to sell them. Initially, this was financed out of general revenues; subsequently, it was financed by a fee on catch quotas. Essentially, each fisherman stated the lowest price that he or she would accept for leaving the industry; the regulators selected those who could be induced to leave at the lowest price, paid the stipulated amount from the fee revenues, and retired their licenses to fish for this species. It wasn't long before a sufficient number of licenses had been retired and the population was protected. Because the program was voluntary, those who left the industry did so only when they felt they had been adequately compensated. Meanwhile, those who paid the fee realized that this small investment would benefit them greatly in the future as the population recovered. A difficult and potentially dangerous pressure on a valuable natural resource had been alleviated by the creative use of an approach that changed the economic incentives.

Toward the end of 1987, however, a new problem emerged. The stock of one species (orange roughy) turned out to have been seriously overestimated by biologists. Since the total allocation of quotas was derived from this estimate, the practical implication was that an unsustainably high level of quotas had been issued; the stock was in jeopardy. The New Zealand government began buying some quotas back from fishermen, but this turned out to be quite expensive with NZ$45 million spent on 15,000 tons of quotas from inshore fisheries.

Faced with the unacceptably large budget implications of buying back a significant amount of quotas, the government ultimately shifted to a percentage-share allocation of quotas. Under this system, instead of owning quotas defined in terms of a specific quantity of fish, fishermen own percentage shares of a total allowable catch. The total allowable catch is determined annually by the government. In this way the government can annually adjust the total allowable catch, based on the latest stock assessment estimates, without having to buy back (or sell) large amounts of quota.

This approach affords greater protection to the stock but increases the financial risk to the fishermen.

The quota markets in New Zealand have been quite active. By 2000, 140,000 leases and 23,000 sales of quotas had occurred. Newell et al. (2005) found that 22 percent of quota owners participated in a market transaction in the first year of the program. By 2000, this number had risen to 70 percent.

Despite this activity, some implementation problems have emerged. Fishing effort is frequently not very well targeted. Species other than those sought (known as "bycatch") may well end up as part of the catch. If those species are also regulated by quotas and the fishermen do not have sufficient ITQs to cover the bycatch, they are faced with the possibility of being fined when they land the unauthorized fish. Dumping the bycatch overboard avoids the fines, but since the jettisoned fish frequently do not survive, this represents a double waste—not only is the stock reduced, but also the harvested fish are wasted.

Managers have also had to deal with "high-grading," which can occur when quotas specify the catch in terms of weight of a certain species, but the value of the catch is affected greatly by the size of the individual fish. To maximize the value of the quota, fishermen have an incentive to throw back the less valuable (typically smaller) fish, keeping only the most valuable individuals. As with bycatch, when release mortality is high, high-grading results in both smaller stocks and wasted harvests.

One possible strategy is simply banning discarding, but due to the difficulties of monitoring and enforcement, that is not as straightforward a solution as it may seem. Kristoffersson and Rickertsen (2009) examine whether a ban on discarding has been effective in the Icelandic cod fishery. They use a model of a fishery with an ITQ program and apply it to the Icelandic cod fishery. They estimate that longline vessels would discard up to 25 percent of the catch of small cod and gillnet vessels up to 67 percent. Their analysis found that quota price did not seem to be an influencing factor, but the existence of a system of quotas and the size of the hold in which the harvested fish are kept do matter. They suggest that to get the "most bang for the buck," enforcement efforts should be directed at gillnet vessels and on fisheries with small hold capacities.

Some fisheries managers have successfully solved both problems by allowing fishermen to cover temporary overages with allowances subsequently purchased or leased from others. As long as the market value of the "extra" fish exceeds the cost of leasing quotas, the fishermen will have an incentive to land and market the fish and the stock will not be placed in jeopardy.

Worldwide, ITQs are currently used by 22 countries to manage hundreds of different species (Table 12.1). The annual global catch taken under ITQs may be as large as a quarter of the global harvest (Arnason, 2012). The fact that ITQ systems are spreading to new fisheries so rapidly suggests that their potential is being increasingly recognized. This expansion does not mean the absence of any concerns. In 1997, the United States issued a moratorium on the implementation of new ITQ programs, which expired in 2002. Issues about the duration of catch shares, whether shareholders need to be active in the fishery and the distributional implications all remain contentious.

Although ITQ systems are far from perfect, frequently they offer the opportunity to improve on traditional fisheries management (see Example 12.2).

EXAMPLE 12.2

The Relative Effectiveness of Transferable Quotas and Traditional Size and Effort Restrictions in the Atlantic Sea Scallop Fishery

Theory suggests that transferable quotas will produce more cost-effective outcomes in fisheries than traditional restrictions, such as minimum legal size and maximum effort controls. Is this theoretical expectation compatible with the actual experience in implemented systems?

In a fascinating study, economist Robert Repetto (2001) examined this question by comparing Canadian and American approaches to controlling the sea scallop fishery off the Atlantic coast. While Canada adopted a transferable quota system, the United States adopted a mix of size, effort, and area controls. The comparison provides a rare opportunity to exploit a natural experiment since scallops are not migratory and the two countries use similar fishing technologies. Hence, it is reasonable to presume that the differences in experience are largely due to the difference in management approaches.

What were the biological consequences of these management strategies for the two fisheries?

- The Canadian fishery was not only able to maintain the stock at a higher level of abundance but it was also able to deter the harvesting of undersized scallops.
- In the United States, stock abundance levels declined and undersized scallops were harvested at high levels.

What were the economic consequences of these differences?

- Revenue per sea-day increased significantly in the Canadian fishery, due largely to the sevenfold increase in catch per sea-day made possible by the larger stock abundance.
- In the United States, fishery revenue per sea-day fell, due not only to the fall in the catch per day that resulted from the decline in stock abundance, but also to the harvesting of undersized scallops.
- Although the number of Canadian quota holders was reduced from nine to seven over a 14-year period, 65 percent of the quota remained in its original hands. The evidence suggests that smaller players were apparently not at a competitive disadvantage.

What were the equity implications?

- Both US and Canadian fisheries have traditionally operated on the "lay" system, which divides the revenue among crew, captain, and owner according to preset percentages, after subtracting certain operating expenditures. This means that all parties remaining in the fishery after regulation shared in the increasing rents.

In these fisheries at least, it seems that the expectations flowing from the theory were borne out by the experience.

Source: Repetto, R. (2001). A natural experiment in fisheries management. *Marine Policy, 25,* 252–264.

In its 2012 annual report, to Congress, NOAA reported that 32 stocks have been rebuilt. Some 41 stocks (19 percent) are still overfished, but that is down from 45 just a year earlier.

Costello, Gaines, and Lynham (2008) examined the global effectiveness of these polices in over 11,000 fisheries from 1950 to 2003. Fisheries with catch share rules, including ITQs, experienced much less frequent collapse than fisheries without them. In fact, they found that by 2003 the fraction of fisheries with ITQs that had collapsed was only half that of non-ITQ fisheries. They suggest that this might be an underestimate since many fisheries with ITQs have not had them for very long. This large study suggests that well-designed property rights regimes (catch shares or ITQs more specifically) may help prevent fisheries collapse and/or help stocks of some species recover. Chu (2009) examined 20 stocks after ITQ programs were implemented and found that 12 of those had improvements in stock size. Eight, however, continued to decline. Apparently, ITQs can sometimes help, but they are no panacea. In the next chapter we will consider whether ITQs can help to conserve different marine species such as whales.

Territorial Use Rights Fisheries (TURFs). An alternative to ITQs is to allocate rights to a specific area for a specific species or group of species, rather than to a portion of the total allowable catch. Such geographic-based rights systems are called territorial use rights fisheries or TURFs. Like ITQs, TURFs typically grant access rights, not ownership rights, to harvesters.

TURFs can allow access to a layer of the water column (such as the bottom of the ocean or the surface, for example) in a specific zone. They could also allow access to a specific oyster bed or a raft for mollusks. They could be granted to individuals, communities, corporations, or even to nations. An economic exclusion zone (EEZ) is a TURF granted to an individual nation.

Early examples of operating TURFs can be found in Japan. These now well-established TURFs allocate zones to local fisher organizations called Fishery Cooperative Assocations (FCAs). Approximately 1,300 FCAs now operate in Japan (Wilen et al., 2012). They can also be found in Chile. With its 3,000 mile shoreline, Chile has created management and exploitation areas (MEAs) along its nearshore. These TURFs help manage the economically important Chilean abalone and sea urchin (Wilen et al., 2012).

TURFs can allow for more economically efficient use of the fishery resource by creating a form of property right, albeit a different property right from that conveyed by an ITQ. Despite their differences, both types of property rights create incentives to protect the future value of the resource, which in turn can incentivize self-enforcement mechanisms. They also can improve the welfare of small fishing communities.

While TURFs do help reduce the open-access problem, the value of a TURF is complicated by the fact that fish are mobile and therefore do not stay in one location. Since a TURF is site specific, its value is impacted by capture outside of the TURF. Obviously, for stocks that do not migrate far, the value of a TURF is enhanced.

Some researchers have suggested that some combination of TURF and ITQ policies may be most efficient. Debate 12.1 considers this question.

ITQs or TURFs? Species, Space, or Both?

DEBATE 12.1

ITQs and TURFs can improve economic efficiency and help protect fisheries from overexploitation. Is one management method better than another? Can they be usefully combined?

Species-based ITQs have proven very popular and they can, in theory, create efficient harveting and conservation incentives. However, in practice enforcement can be challenging and they suffer from several externalities. Some of the most prominent externalties, including gear impacts on ecosystems, spatial externalities and cross-species interactions, might actually be increased by ITQs. Let's see how.

Typically the total allowable catch (TAC) is divided amongst several, perhaps numerous, owners. Although they do not compete over the size of their catch (since that is fixed by their catch share), they do still compete over the timing of that catch. Timing might matter a great deal when the most productive harvesting periods (in terms of reducing the private effort required per unit catch) turn out to be precisely the periods that impose the largest external costs (say by increasing the likelihood of bycatch or negatively impacting the juvenile stock). As such, they help solve one problem (assuring a sustainable total catch), while creating another (encouraging a harvest timing that increases external costs).

The Coase theorem (Chapter 2) suggests that these ownership rights should, in principle, create incentives to solve the remaining externalities, as well, but in practice, the transactions costs of such negotiations are apparently prohibitively high.

What about TURFs? TURFs help solve the problem of managing harvests over time and space and can help protect sensitive areas given that an individual or group has sole rights to that area. Local cooperatives have the advantage of being able in principle to manage interspecies interactions and habitat destruction, but in practice TURFs tend to suffer from conflict and coordination problems. Another common criticism of TURFs is that the scale must match the range of the species and many TURFs do not (or cannot) achieve this size.

Rather than framing the issue as whether ITQs or TURFs are the best choice, it may be that each has its own niche. Certainly, in developing countries with weak institutional structures, TURFs offer many advantages over species-based ITQs. TURFs also may be most appropriate for small, local populations. On the other hand, ITQs have been used successfully for many marine fisheries. Clearly, one size does not fit all for fisheries policy.

Source: Wilen, J. E., Cancino, J., & Uchida, H. (Summer 2012), The economics of territorial use rights fisheries, or TURFs. *Review of Environmental Economics and Policy*, *6*(2), 237–257.

Aquaculture

Having demonstrated that inefficient management of the fishery results from treating it as an open-access resource, one obvious solution is to allow some fisheries to be privately held. This approach can work when the fish are not very mobile, when they can be confined by artificial barriers, or when they instinctively return to their place of birth to spawn.

The advantages of such a move go well beyond the ability to preclude overfishing. The owner is encouraged to invest in the resource and undertake measures that will increase the productivity (yield) of the fishery. (For example, adding certain nutrients to the water or controlling the temperature can markedly increase the yields of some species.) The controlled raising and harvesting of fish is called *aquaculture*. Probably the highest yields ever attained through aquaculture resulted from using rafts to raise mussels. Some 300,000 kilograms per hectare of mussels, for example, have been raised in this manner in the Galician bays of Spain. This productivity level approximates those achieved in poultry farming, widely regarded as one of the most successful attempts to increase the productivity of farm-produced animal protein.

Japan became an early leader in aquaculture, undertaking some of the most advanced aquaculture ventures in the world. The government has been supportive of these efforts, mainly by creating private property rights for waters formerly held in common. The governments of the prefectures (which are comparable to states in the United States) initiate the process by designating the areas to be used for aquaculture. The local fishermen's cooperative associations then partition these areas and allocate the subareas to individual fishermen for exclusive use. This exclusive control allows the individual owner to invest in the resource and to manage it effectively and efficiently.

Another market approach to aquaculture involves *fish ranching* rather than *fish farming*. Whereas fish farming involves cultivating fish over their lifetime in a controlled environment, fish ranching involves holding them in captivity only for the first few years of their lives.

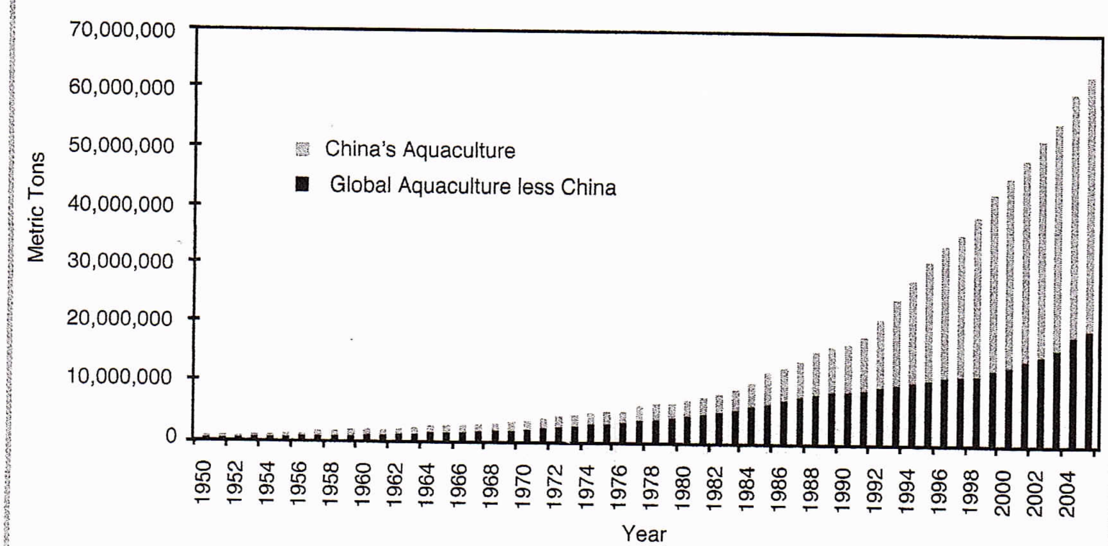
Fish ranching relies on the strong homing instincts in certain fish, such as Pacific salmon or ocean trout, which permits their ultimate return and capture. The young salmon or ocean trout are hatched and confined in a convenient catch area for approximately 2 years. When released, they migrate to the ocean. Upon reaching maturity, they instinctually return to the place of their births, where they are harvested.

Fish farming has certainly affected the total supply of harvested fish. Aquaculture is currently the fastest-growing animal food production sector. In 1970, it was estimated that 3.9 percent of fish consumed globally were raised on farms. By 2008, this proportion had risen to 46 percent. (Between 1970 and 2008, global per capita supply of farm-raised fish increased from 1.5 pounds to 17.2 pounds.)

In China, growth rates in aquaculture have been even higher and aquaculture represents more than two-thirds of fisheries production. China has become the largest producer (and exporter) of seafood in the world (see Figure 12.7), now producing 62 percent of the global supply of farmed fish. Shrimp, eel, tilapia, sea bass, and carp are all intensively farmed. While the top five producers (in volume) of fish from aquaculture in 2006 were China, India, Vietnam, Thailand, and Indonesia, growth rates in aquaculture production were highest in Uganda, Guatemala, Mozambique, Malawi, and Togo.[10]

Aquaculture is certainly not the answer for all fish. Today, it works well for certain species, but other species will probably never be harvested domestically. Furthermore, fish farming can create environmental problems (see Debate 12.2). Nonetheless, it is comforting to know that aquaculture can provide a safety valve in some regions and for some fish and in the process take some of the pressure off the overstressed natural fisheries. The challenge will be to keep aquaculture sustainable.

FIGURE 12.7 China's Rising Share of Global Aquaculture



Source: FAO Statistics and Information Service of the Fisheries and Aquaculture Department. 2013. Aquaculture production (Quantities and values) 1950-2011. FISHSTAT Plus - Universal software for fishery statistical time series [online or CD-ROM]. Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/fishery/statistics/software/fishstat/en.

[10]Food and Agriculture Organization of the United Nations. *State of the World's Fisheries and Aquaculture* (2008) ftp://ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf.

DEBATE 12.2 Aquaculture: Does Privatization Cause More Problems Than It Solves?

Privatization of commercial fisheries, namely through fish farming, has been touted as a solution to the overfishing problem. For certain species, it has been a great success. Some types of shellfish, for example, are easily managed and farmed through commercial aquaculture. For other species, however, the likelihood of success is not so clear-cut.

Atlantic salmon is a struggling species in the northeastern United States and for several rivers, is listed as "endangered." Salmon farming takes the pressure off of the wild stocks. Atlantic salmon are intensively farmed off the coast of Maine, in northeastern Canada, in Norway, and in Chile. Farmed Atlantic salmon make up almost all of the farmed salmon market and more than half of the total global salmon market. While farmed salmon offer a good alternative to wild salmon and aquaculture has helped meet the demand for salmon from consumers, it is not problem-free.

Farmed fish escapees from the pens threaten native species, pollution that leaks from the pens creates a large externality, and pens that are visible from the coastline degrade the view of coastal residents. The crowded pens also facilitate the prevalence and diffusion of several diseases and illnesses, such as sea lice and salmon anemia. Antibiotics used to keep the fish healthy are considered dangerous for humans. Diseases in the pens can also be transferred to wild stocks. In 2007, the Atlantic Salmon Federation and 33 other conservation groups called on salmon farms to move their pens farther away from sensitive wild stocks.

And the concerns do not end there. Currently, many small species of fish, like anchovies or herring, are being harvested to feed carnivorous farmed fish. Scientists argue that this is not an efficient way to produce protein, since it takes 3–5 pounds of smaller fish to produce 1 pound of farmed salmon.

Pollution externalities associated with the increased production include contaminated water supplies for the fish ponds and heavily polluted wastewater. Some farmers raising their fish in contaminated water have managed by adding illegal veterinary drugs and pesticides to the fish feed, creating food safety concerns. Some tested fish flesh has been found to contain heavy metals, mercury, and flame retardants. In 2007, the United States refused 310 import shipments of seafood; 210 of those were drug-chemical refusals.

While solving some problems, intensive aquaculture has created others. Potential solutions include open-ocean aquaculture (moving pens out to sea), closing pens, monitoring water quality, and improving enforcement. Clearly, sole-ownership to the fishery isn't a silver bullet when externalities are prevalent.

Sources: Atlantic Salmon Federation; Fishstat FAO 2007; Barboza, D. (2007, December 15). China's seafood industry: Dirty water, dangerous fish. *New York Times*.

Subsidies and Buybacks

Excess fleet capacity or overcapitalization is prevalent in many commercial fisheries. Overcapacity encourages overfishing. Many subsidies exacerbate this effect by encouraging overcapacity and overcapitalization. Fuel subsidies, tax exemptions, fish price supports, and grants for new vessels are common forms of subsidies in fisheries. By enhancing profits, these subsides create perverse incentives to continue fishing even while stocks are declining. Over $10 billion in subsidies were provided in 2000, 80 percent of which came from developing countries (World Bank, 2009).

A rather different type of subsidy is intended to discourage overfishing. If vessel owners do not have alternative uses for their vessels, they may resist catch restrictions or other measures meant to help depleted stocks. Management options have included buyback or, equivalently, decommissioning subsidies to reduce fishing capacity. In 2004, the US government spent $100 million to buy out 28 of the 260 Alaskan snow crab fishery vessels. The EU has also proposed spending an additional €272 million on decommissioning (Clark et al., 2005). Payments used to buy out excess fishing capacity are useful subsidies in that they reduce overcapacity, but if additional capacity seeps in over time, they are not as effective as other management measures. Clark et al. (2005) also note that if fishermen come to anticipate a buyback, they may acquire more vessels than they otherwise would have, which would lead to even greater levels of overcapacity.

Marine Protected Areas and Marine Reserves

Regulating only the amount of catch leaves the type of gear that is used and locations where the harvests take place uncontrolled. Failure to control those elements can lead to environmental degradation of the habitat on which the fishery depends even if catch is successfully regulated. Some gear may be particularly damaging, not only to the targeted species (e.g., by capturing juveniles that cannot be sold, but that don't survive capture), but also to nontargeted species (bycatch). Similarly, harvesting in some geographic areas (such as those used for spawning) might have a disproportionately large detrimental effect on the sustainability of the fishery.

Conservation biologists have suggested complementing current policies with the establishment of a system of marine protected areas (MPAs). The US federal government defines MPAs as "any area of the marine environment that has been reserved by federal, state, tribal, territorial, or local laws or regulations to provide lasting protection for part or all of the natural and cultural resources therein."[11] Restrictions range from minimal to full protection. A marine reserve, a marine protected area with full protection, is an area that prohibits harvesting and enjoys a very high level of protection from other threats, such as pollution.

Biologists believe that marine protected areas can perform several maintenance and restorative functions. First, they protect *individual species* by preventing harvest within the reserve boundaries. Second, they reduce *habitat damage* caused by fishing gear or practices that alter biological structures. Third, in contrast to quotas on single species, reserves can promote *ecosystem balance* by protecting against the removal of ecologically pivotal species (whether targeted species or bycatch) that could throw an ecosystem out of balance by altering its diversity and productivity (Palumbi, 2002).

[11] For information and maps of marine protected areas of the United States, see www.mpa.gov.

Reducing harvesting in these areas protects the stock, the habitat, and the ecosystem on which it depends. This protection results in a larger population and, ultimately, if the species swim beyond the boundaries of the reserve, larger catches in the remaining harvest areas.

Simply put, reserves promote sustainability by allowing the population to recover. Their relationship to the welfare of current users, however, is less clear. Proponents of MPAs suggest that they can promote sustainability in a win–win fashion (meaning current users benefit as well). This is an important point because users who did not benefit might mount political opposition to marine reserve proposals, thereby making their establishment very difficult.

Would the establishment of a marine protected area maximize the present value of net benefits for fishermen? If MPAs work as planned, they reduce harvest in the short run (by declaring areas previously available for harvest off-limits), but they increase it in the long run (as the population recovers). However, the delay would impose costs. (Remember how discounting affects present value?) To take one concrete example of the costs of delay, harvesters may have to pay off a mortgage on their boat. Even if the bank grants them a delay in making payments, total payments will rise. So, by itself, a future rise in harvests does not guarantee that establishing the reserve maximizes present value unless the rise in catch is large enough and soon enough to compensate for the costs imposed by the delay.[12]

Since the present value of this policy depends on the specifics of the individual cases, a case study can be revealing. In an interesting case study of the California sea urchin industry, Smith and Wilen (2003) state the following:

> *Our overall assessment of reserves as a fisheries policy tool is more ambivalent than the received wisdom in the biological literature. . . . We find . . . that reserves can produce harvest gains in an age-structured model, but only when the biomass is severely overexploited. We also find . . . that even when steady state harvests are increased with a spatial closure, the discounted returns are often negative, reflecting slow biological recovery relative to the discount rate. (p. 204)*

This certainly does not mean that MPAs or marine reserves are a bad idea! In some areas, they may be a necessary step for achieving sustainability; in others, they may represent the most efficient means of achieving sustainability. It does mean, however, that we should be wary of the notion that they always create win–win situations; sacrifices by local harvesters might be required. MPA policies must recognize the possibility of this burden and deal with it directly, not just assume it doesn't exist.

Some international action on marine reserves is taking place as well. The 1992 international treaty, called the Convention on Biological Diversity, lists as one of its goals the conservation of at least 10 percent of the world's ecological regions,

[12]The distribution of benefits and costs among current fishermen also matters. Using a case study on the Northeast Atlantic Cod fishery, Sumaila and Armstrong (2006) find that the distributional effects of MPAs depend significantly on the management regime that was in place at the time of the development of the MPA and the level of cooperation in the fishery.

including, but not limited to, marine ecoregions. Progress has been significant for terrestrial ecoregions, but less so for coastal and marine ecoregions. In 2010, however, in one noteworthy event, the United Kingdom created the largest marine reserve in the world by setting aside the Chagos Archipelago, which stretches 544,000 square kilometers in the Indian Ocean, as a protected area.

The 200-Mile Limit

The final policy dimension concerns the international aspects of the fishery problem. Obviously, the various policy approaches to effective management of fisheries require some governing body to have jurisdiction over a fishery so that it can enforce its regulations.

Currently, this is not the case for many of the ocean fisheries. Much of the open water of the oceans is a common-pool resource to governments as well as to individual fishermen. No single body can exercise control over it. As long as that continues to be the case, the corrective action will be difficult to implement. In recognition of this fact, there is now an evolving law of the sea defined by international treaties. One of the concrete results of this law, for example, has been some limited restrictions on whaling. Whether this process ultimately yields a consistent and comprehensive system of management remains to be seen, but it is certainly an uphill battle.

Countries bordering the sea have taken one step by declaring that their ownership rights extend some 200 miles out to sea. Within these areas, the countries have exclusive jurisdiction and can implement effective management policies. These zones are essentially very large TURFs. These "exclusive zone" declarations have been upheld and are now firmly entrenched in international law. Thus, very rich fisheries in coastal waters can be protected, while those in the open waters await the outcome of an international negotiations process.

Preventing Poaching

Poaching (illegal harvesting) can introduce the possibility of unsustainability even when a legal structure to protect the population has been enacted. For example, in 1986 the International Whaling Commission set a ban on commercial whaling, but under a loophole in this law, Japan had continued to kill hundreds of whales each year. In November 2007, a fleet embarked on a 5-month hunt in the Antarctic despite numerous international protests. While originally intending to target humpback whales, in response to the protests, Japan eventually stopped harvesting that species. Since humpback whales are considered "vulnerable," commercial hunts have been banned since 1966, but Japan had claimed that harvests for research were not covered by this ban.

Bluefin tuna is another very valuable commerical species that is threatened and has been brought under international control. The population of bluefin tuna has plummeted 85 percent since 1970, with 60 percent of that loss occurring in the last decade. Japan is the largest consumer of bluefin tuna, which is prized for sushi. Fleets from Spain, Italy, and France are the primary suppliers.

In the United States, the National Marine Fisheries Service has proposed a catch-share program for the US portion of the International Commission for the Conservation of Atlantic Tunas (ICCAT) quota of endangered bluefin tuna. If implemented, it remains to be seen whether this type of program can work well for such a highly migratory species.

A rather different approach to protect the species was also tried in the international forum. In 2009, a petition to ban trade in the Atlantic bluefin tuna went before the U.N. Convention on International Trade in Endangered Species (CITES). This was the first time that a major commercial fishery has been addressed by CITES. While conservationists and biologists supported the CITES listing, many industry groups were opposed. The National Fisheries Institute president, John Connelly, wrote in opposition, "Commercially-exploited aquatic species are fundamentally different from the other species that CITES regulates . . . Unlike these other species, fish and seafood stocks are not generally threatened with biological extinction. While they can and do become overfished, the resulting loss of return on investment for fishermen prevents them from driving commercial fish stocks toward biological extinction" (Gronewold, 2009). In early 2010, CITES voted against the ban. In January 2011, a record price was set for a northern bluefin. A giant 754-pound bluefin brought 32.5 million yen, or nearly $400,000. Do you think this price is a sufficient incentive to protect the bluefin tuna from extinction? Why or why not? See Debate 12.3.

DEBATE 12.3 Bluefin Tuna: Is Its High Price Part of the Problem or Part of the Solution?

The International Commission for the Conservation of Atlantic Tunas (ICCAT) is responsible for the conservation of highly migratory species, including several species of tuna. ICCAT reports fish biomass as well as catch statistics and is responsible for setting total allowable catch by species each year.

Since ICCAT has never successfully enforced their quotas, it is not clear that they have a credible enforcement capability. Monitoring statistics consistently show catch well above the TAC.

Additionally, international pressure from the fishing industry frequently results in a TAC higher than scientists recommend. In 2009, for example, having reviewed the current biomass statistics, which showed the current stock to be at less than 15 percent of its original stock, ICCAT scientists recommended a total suspension of fishing. Ignoring their scientists' recommendation, ICCAT proceeded to set a quota of 13,500 tons. They did, however, also agree to establish new management measures for future years that will allow the stock to rebuild with an estimated 60 percent degree of confidence. While that sounds good, it turns out that if enforcement is less than perfect, and the resulting catch is above 13,500, the probability that the stock will recover cannot reach the 60 percent level by 2022 (Table 12.2).

TABLE 12.2 Probabilities of Stock Rebuilding at SSBF0.1 by Years and TAC Levels

	Percent				
TAC	2010	2013	2016	2019	2022
0	0	2	25	69	99
2,000	0	1	21	62	99
4,000	0	1	18	55	99
6,000	0	1	14	47	97
8,000	0	0	11	40	92
10,000	0	0	9	33	84
12,000	0	0	6	26	73
13,500	0	0	5	21	63
14,000	0	0	4	20	59
16,000	0	0	3	14	46
18,000	0	0	2	10	34
20,000	0	0	1	6	24

Note: Grey color highlights the catch at which the 60 percent probability would not be achieved.

Source: Report of the 2010 Atlantic bluefin tuna stock assessment session (Table 1); ICCAT, www.iccat.int/en

Sources: International commission for the conservation of Atlantic tunas 2009 annual iccat meeting press release 16, November 2009; ICCAT, www.iccat.org; Gronewold, G. (October 14, 2009). Is the bluefin tuna an endangered species? *Scientific American,* Retrieved from http://www.scientificamerican.com/article.cfm?id=bluefin-tuna-stocks-threatened-cites-japan-monaco; Draft amendment 7 to the consolidated Atlantic highly migratory species fishery management plan, *National Marine Fisheries Service*, August 2013, Retrieved from http://www.scribd.com/doc/161801821/NOAA-Draft-Bluefin-Tuna-Amendment.

Summary

Unrestricted access to commercially valuable species will generally result in overexploitation. This overexploitation, in turn, results in overcapitalization, depressed incomes for harvesters, and depleted stocks. Even extinction of the species is possible, particularly for populations characterized by easy, low-cost extraction. Where extraction costs are higher, extinction is unlikely, even with unrestricted access.

Both the private and public sectors have moved to ameliorate the problems associated with past mismanagement of commercial fisheries. By reasserting private property rights, many countries have stimulated the development of aquaculture. Governments in Canada and the United States have moved to limit overexploitation of the Pacific salmon. International agreements have been instituted to place limits on whaling. It is doubtful that these programs fully satisfy the efficiency criterion, although it does seem clear that more sustainable catches will result.

Creative strategies for sharing the gains from moving to an efficient level of harvest could prove to be a significant weapon in the arsenal of techniques designed to protect a broad class of biological resources from overexploitation. An increasing reliance on individual transferable quotas (ITQs) and TURFs offers the possibility of preserving stocks without jeopardizing the incomes of those men and women currently harvesting those stocks. Strengthening property rights is a key component in generating both efficient and sustainable harvests.

It would be folly to ignore barriers to further action, such as the reluctance of individual harvesters to submit to many forms of regulation, the lack of a firm policy governing open-ocean waters, and the difficulties of enforcing various approaches. Whether these barriers will fall before the pressing need for effective management remains to be seen.

In this chapter we have focused on fisheries as an example of a renewable biological resource, but the models and the insights that flow from them can be used to think about managing other wildlife populations as well. This topic will be taken up in the next chapter.

Discussion Questions

1. Is the establishment of the 200-mile limit a sufficient form of government intervention to ensure that the tragedy of the commons does not occur for fisheries within the 200-mile limit? Why or why not?
2. With discounting it is possible for the efficient fish population to fall below the level required to produce the maximum sustained yield. Does this violate the sustainability criterion? Why or why not?

Self-Test Exercises

1. Assume that the relationship between the growth of a fish population and the population size can be expressed as $g = 4P - 0.1P^2$, where g is the growth in tons and P is the size of the population (in thousands of tons). Given a price of \$100 a ton, the marginal benefit of smaller population sizes (and hence larger catches) can be computed as $20P - 400$. (a) Compute the population size that is compatible with the maximum sustainable yield. What would be the size of the annual catch if the population were to be sustained at this level? (b) If the marginal cost of additional catches (expressed in terms of the population size) is $MC = 2(160 - P)$, what is the population size that is compatible with the efficient sustainable yield?

2. Assume that a local fisheries council imposes an enforceable quota of 100 tons of fish on a particular fishing ground for one year. Assume further that 100 tons per year is the efficient sustained yield. When 100 tons have been caught, the fishery would be closed for the remainder of the year. (a) Is this an efficient solution to the common property problem? Why or why not? (b) Would your answer be different if the 100-ton quota were divided into 100 transferable quotas, each entitling the holder to catch 1 ton of fish, and distributed among the fishermen in proportion to their historical catch? Why or why not?
3. In the economic model of the fishery developed in this chapter, compare the effect on fishing effort of an increase in cost of a fishing license with an increase in a per-unit tax on fishing effort that raises the same amount of revenue. Assume the fishery is private property. Repeat the analysis assuming that the fishery is a free-access common property resource.
4. When trying to reduce the degree of inefficiency from an open-access fishery, would a regulation that increases the marginal cost of fishing effort by banning certain types of gear or a tax on effort be equally efficient? Why or why not?
5. a. In the typical economic model of an efficient fishery, would a fall in the price of fish generally result in a larger or a smaller sustainable harvest? Why?
   b. Suppose the fishery allowed free access. Would a fall in the price of fish generally result in a larger or a smaller harvest? Why?
6. Suppose that a particular fishery experiences a technological change such that the fixed cost of fishing increases, but the marginal cost of fishing decreases. The change is such that the before and after total cost curves cross at an effort level higher than that associated with the before efficient sustained yield, but lower than the free-access level of effort.
   a. What would the effect of this technological change be on the static efficient level of effort and the size of the static efficient level of harvest? Would they increase or decrease or are the effects ambiguous?
   b. What would the effect of this technological change be on the level of effort and the size of the harvest in a free-access fishery? Would they increase or decrease or are the effects ambiguous?

Further Reading

Acheson, J. M. (2003). *Capturing the commons: Devising institutions to manage the Maine lobster industry*. Hanover, NH: University Press of New England. An impressive synthesis of theory and empirical work, combined with an insider's knowledge of the institutions and the people who run them, makes this a compelling examination of the history of one of America's most important fisheries.

Adler, J. H., & Stewart, N. (2013). Learning how to fish: Catch shares and the future of fisheries conservation. *UCLA Journal of Environmental Law & Policy*, *31*(1). A useful summary of the history, law, and economics of catch shares.

Clark, C. W. (1990). *Mathematical bioeconomics: The optimal management of renewable resources*, 2nd ed. New York: Wiley-Interscience. Careful development of the mathematical models that underlie current understanding of the exploitation of renewable resources under a variety of property rights regimes.

NOAA Catch Share Policy: Executive Summary 2013. Retrieved from http://www.nmfs.noaa.gov/sfa/domes_fish/catchshare/docs/noaa_cs_policy.pdf. A useful review of US Fisheries Policy. Review of Environmental Economics and Policy Volume 6 Issue 2 Sum 2012. Contains several summary articles from the Symposium: Rights-Based Fisheries Management.

Schlager, E., & Ostrom, E. (1992). Property right regimes and natural resources: A conceptual analysis. *Land Economics*, *68*, 249–262. A conceptual framework for analyzing a number of property rights regimes; the authors use this framework to interpret findings from a number of empirical studies.

Additional References and Historically Significant References are available on this book's Companion Website: http://www.pearsonhighered.com/tietenberg/

Appendix

The Harvesting Decision: Fisheries

Defining the efficient sustainable yield for a fishery begins with a characterization of the biological relationship between the growth for the biomass and the size of the biomass. The standard representation of this relationship is

$$g = rS\left(1 - \frac{S}{k}\right), \tag{1}$$

where
g = the growth rate of the biomass,
r = the intrinsic growth rate for this species,
S = the size of the biomass, and
k = the carrying capacity of the habitat.

Since we want to choose the most efficient *sustained* yield, we must limit the possible outcomes we shall consider to those that are sustainable. Here we define a sustainable harvest level, h_S, as one that equals the growth of the population. Hence:

$$h_s = rS\left(1 - \frac{S}{k}\right). \tag{2}$$

The next step is to define the size of the harvest as a function of the amount of effort expended. This is traditionally modeled as

$$h = qES, \tag{3}$$

where
q = a constant (known as the "catchability coefficient") and
E = the level of effort.

The next step is to solve for sustained yields as a function of effort. This can be derived using a two-step procedure. First, we express S in terms of E. Then we use this newly derived expression for S along with the relationship in Equation (3) to derive the sustained yield expressed in terms of effort.

To define S in terms of E, we can substitute Equation (3) into Equation (2):

$$qES = rS\left(1 - \frac{S}{k}\right). \tag{4}$$

Rearranging terms yields

$$S = k\left(1 - \frac{qE}{r}\right). \tag{5}$$

Using $S = h/qE$ from Equation (3) and rearranging terms to solve for h yields

$$h_s = qEk - \frac{q^2kE^2}{r}. \tag{6}$$

It is now possible to find the maximum sustainable effort level by taking the derivative of the right-hand side of Equation (6) with respect to effort (E) and setting the result equal to zero.

The maximum condition is

$$qk - 2\frac{q^2kE}{r} = 0. \tag{7}$$

So

$$E_{msy} = \frac{r}{2q}, \tag{8}$$

where

E_{msy} = the level of effort that is consistent with the maximum sustained yield.

Can you see how to solve for the maximum sustainable yield, h_{msy}? (*Hint*: Remember how the maximum sustained yield was defined in terms of effort in Equation (6)?)

To conduct the economic analysis, we need to convert this biological information to a net benefits formulation. The benefit function can be defined by multiplying Equation (6) by P, the price received for a unit of harvest. Assuming a constant marginal cost of effort, a, allows us to define total cost as equal to aE. Subtracting the total cost of effort from the revenue function produces the net benefits function:

$$\text{Net benefits} = PqEk - \frac{Pq^2kE^2}{r} - aE. \tag{9}$$

Since the efficient sustained effort level is the level that maximizes Equation (9), we can derive it by taking the derivative of Equation (9) with respect to effort (E) and setting the derivative equal to zero:

$$Pqk - \frac{2Pkq^2E}{r} - a = 0. \tag{10}$$

Rearranging terms yields

$$E = \frac{r}{2q}\left(1 - \frac{a}{Pqk}\right). \tag{11}$$

Note that this effort level is smaller than that needed to produce the maximum sustainable yield. Can you see how to find the efficient sustainable harvest level? Finally, we can derive the free-access equilibrium by setting the net benefits function in Equation (9) equal to zero and solving for the effort level.

Rearranging terms yields

$$E = \frac{r}{q}\left(1 - \frac{a}{Pqk}\right). \tag{12}$$

Note that this is larger than the efficient sustained level of effort. It may or may not be larger than the level of effort needed to produce the maximum sustained yield. That comparison depends on the specific values of the parameters.